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# Metal flow in rotary splitting of circular disk

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**Abstract**

An experimental study of rotary splitting of circular disk was conducted to survey the effect of forming parametars on the metal flow in rotary spritting. It was found that the radial force $F_r$ increases with the increase in the initial blank thickness $t_0$, the feed rate of roller $v$ and the apex angle of forming roller $\alpha$. It was also found that the length of the straight part of formed V-shaped profile $l_s$ increases with the increase in the initial blank thickness $t_0$ and the apex angle of forming roller $\alpha$.


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*Keywords:* Rotary forming; Rotary splitting; Circular disk

## 1. Introduction

Rotary forming is a method of forming various profiles from circular rods, tubes and sheet-metal blanks by a rotary compressive process. Rotary splitting is a rotary forming process applied to manufacturing pulleys and flywheels from circular disk blanks. A circular disk as workpiece is rotating at a constant number of revolutions with an electric motor, as shown in Fig. 1. A forming roller with an apex angle of $\alpha$ is fed with a constant feed rate $v$ along a path perpendicular to the axis of circular disk. When the forming roller comes into contact with the outer cylindrical surface of the rotating workpiece, it also begins rotating due to the friction between the forming roller and the workpiece. Simultaneously the rotating workpiece is split by the forming roller with the apex angle of $\alpha$.

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Kaftanğlu et al. (1987), Bauer (1990) and Huang et al. (2008) tried to investigate the metal flow in rotary splitting, however, their deformation models were not for rotary splitting but for rotary compression. A fundamental understanding of the metal flow in rotary splitting is essential to apply this rotary forming process widely to the production of various machine parts without a trial and error approach.

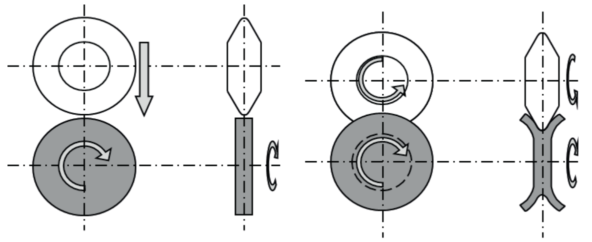

Fig.1. Rotary splitting of a circular disk using a driving blank and a driven forming roller.

## 2. Experimental procedure

A circular blank disk of outer diameter of 64 mm and initial thickness of $t_0$ rotated at a constant number of revolutions of 72 rpm with the mandrel. A forming roller of outer diameter of 80 mm, round-off radius of $\rho_R$ = 0.2 mm and apex angle of $\alpha$ split the circular disk as workpiece with the feed rate of forming roller $v$ to form a bifurcated V-shaped profile of angle of $\alpha'$ and root radius of $\rho'$. The working conditions in the experiment are listed in Table 1. Three levels of the initial thickness of the blank $t_0$, the apex angle of the forming roller $\alpha$ and the feed rate of the roller $v$ were selected to conduct the analysis of variance F-test based on the design of experiments. The forming forces, radial force $F_r$, axial force $F_a$ and tangential force $F_t$, were measured with strain gauges attached to the roller holder. The shape and dimensions of formed V-shaped profile were measured with a measuring microscope. The material of the blank disk was commercially pure aluminum, JIS A1050. The experiments of rotary splitting were carried out at room temperature after application of machine oil as lubricant.

Table 1. Working conditions in the experiment, for symmetrical forming.

| Forming parameter | |
|---|---|
| Initial thickness of blank, $t_0$ [mm] | 3, 6, 9 |
| Apex angle of forming roller, $\alpha$ [deg.] | 30, 45, 60 |
| Feed rate of forming roller, $v$ [mm/rev] | 0.1, 0.3, 0.5 |

## 3. Results and discussion

### *3.1. Symmetric forming*

The forming roller came into contact with the outer cylindrical surface of the workpiece at the symmetric position along the thickness in order to investigate the effect of forming parameters on the metal flow in rotary splitting of circular disk. The stress-strain relation of the material used in the experiment for symmetric forming was $\sigma = 156\varepsilon^{0.184}$ MPa. The maximum penetration of the forming roller into the workpiece was $s$ = 6 mm. The forming forces and dimensions of formed product were measured at this maximum penetration.

The radial forces $F_r$, normalized by the maximum radial force through the experiments, are shown in Fig. 2(a) for the apex angle of forming roller of $\alpha$ = 60° and Fig. 2(b) for the feed rate of forming roller of $v$ = 0.5 mm/rev, respectively. These figures show that the radial force $F_r$ increases with the increase in the initial thickness of blank disk $t_0$, the feed rate of forming roller $v$ and the apex angle of forming roller $\alpha$. An analysis of variance F-test based on the design of experiments was conducted to investigate the effect of the forming parameters listed in Table 1 on the radial force $F_r$. The contributions of the initial thickness of blank disk $t_0$, the feed rate of forming roller $v$ and the apex angle of forming roller $\alpha$ to the radial force $F_r$ are 47.2%, 23.2% and 17.7%, respectively. The effect of these forming parameters on the radial force $F_r$ is significant with the significant level of 1%.

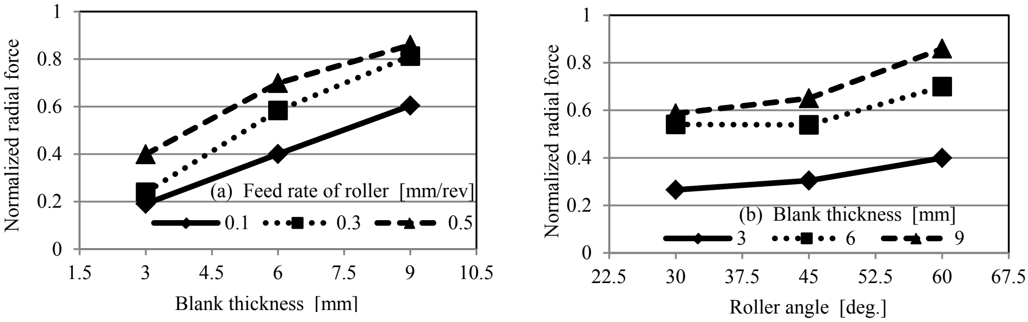


Fig. 2. Effect of initial blank thickness $t_0$, apex angle of forming roller $\alpha$ and feed rate of roller $v$ on the radial force $F_r$, (a) $\alpha$ = 60°, (b) $v$ = 0.5 mm/rev.

The flank surface of formed V-shaped profile consists of a straight part and a curved part. The length of the straight part of formed V-shaped profile $l_s$ can be seen in Fig. 3(a) for the initial thickness of blank disk of $t_0$ = 6 mm and Fig. 3(b) for the feed rate of forming roller of $v$ = 0.1 mm/rev, respectively. The length of straight part of formed V-shaped profile $l_s$ increases with the increase in the initial thickness of blank disk $t_0$, the apex angle of forming roller $\alpha$ and the feed rate of forming roller $v$. The contributions of the initial thickness of blank disk $t_0$ and the apex angle of forming roller $\alpha$ to the length of straight part of formed V-shaped profile $l_s$ are 77.6% and 18.0%, respectively. While the contribution of the feed rate of forming roller $v$ to the length of the straight part of formed V-shaped profile $l_s$ is 1.0%, this effect is significant with the significant level of 1%.

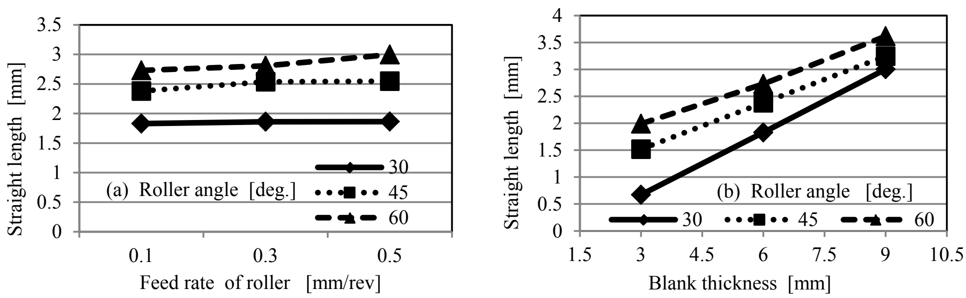


Fig. 3. Effect of initial blank thickness $t_0$, apex angle of forming roller $\alpha$ and feed rate of roller $v$ on the length of straight part of formed V-shaped profile $l_s$, (a) $t_0$ = 6 mm, (b) $v$ = 0.1 mm/rev.

The measured formed angles of V-shaped profile $\alpha'$ are shown in Fig. 4(a) for the apex angle of forming roller of $\alpha$ = 30° and Fig. 4(b) for $\alpha$ = 45°, respectively. These graphs show that the angle of formed V-shaped profile $\alpha'$ increases with the increase in the feed rate of forming roller $v$, however, it seems that the initial thickness of blank disk $t_0$ does not affect the angle of formed V-shaped profile $\alpha'$. The springback phenomenon of formed angle of V-shaped profile is observed because the values of formed angle $\alpha'$ are less than the measured values of apex angles of forming roller, $\alpha$ = 30.03° and $\alpha$ = 45.03°, respectively. The change of formed angle $\Delta\alpha = \alpha - \alpha'$ equivalent to the springback increases with the decrease in the feed rate of forming roller $v$, as shown in Fig.4.

Since the angle of formed V-shaped profile $\alpha'$ is less than the apex angle of forming roller $\alpha$ from Fig. 4, the straight part of the flank surface of formed V-shaped profile contacts the forming roller with the apex angle $\alpha$ at the maximum penetration of forming roller of $s$ = 6 mm. While the contribution of the feed rate of forming roller $v$ to the length of the straight part of formed V-shaped profile $l_s$ is significant with the significant level of 1 %, its effect is not so significant as shown in Fig. 3(a). The forming force in rotary forming depends on the area of contact between the forming roller and the workpiece during the process. The area of contact between the forming roller and the workpiece during the process is also dependent on the length of straight part of the flank surface of formed V-shaped profile and the contact length along the tangential direction. The area of contact in rotary splitting $A_p$ can be calculated with the measured length of straight part of formed V-shaped profile and the equation of contact length in rotary forming proposed by Hayama (1967) as shown in Fig. 5(a) for the apex angle of forming roller of $\alpha = 45°$ and Fig. 5(b) for $\alpha = 60°$, respectively. The area of contact in Fig. 5 is projected on the plane perpendicular to the radial direction of forming roller. It can be noted that the contact area $A_p$ increases with the increase in the apex angle of forming roller $\alpha$, the feed rate of forming roller $v$ and the initial thickness of blank disk $t_0$ from Fig. 5. The contributions of the apex angle of forming roller $\alpha$, the feed rate of forming roller $v$ and the initial thickness of blank disk $t_0$ to the contact area between the forming roll and the workpiece in rotary splitting $A_p$ are 38.9%, 28.1% and 25.1%, respectively, with the significant level of 1%. Therefore it can be explained that the feed rate of forming roller $v$ affect the radial force $F_r$ considerably, though the effect of feed rate $v$ on the length of straight part of formed V-shaped profile $l_s$ is not so significant.

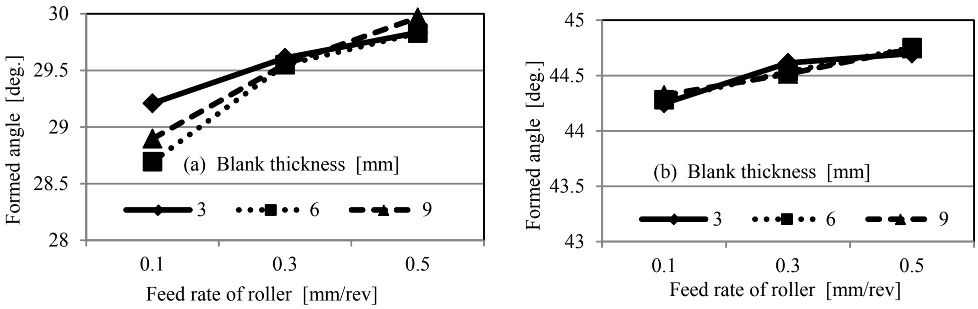


Fig. 4. Effect of initial blank thickness $t_0$ and feed rate of roller $v$ on the formed angle of V-shaped profile $\alpha'$, (a) $\alpha = 30°$, (b) $\alpha = 45°$.

The average values of the wall thickness of the straight part of the flank surface of formed V-shaped profile $t_w$ are shown in Fig. 6(a) for the apex angle of forming roller of $\alpha = 30°$ and Fig. 6(b) for $\alpha = 60°$, respectively. The wall thickness of the straight part of the flank surface of formed V-shaped profile is independent on the apex angle of forming roller $\alpha$ and the feed rate of forming roller $v$, however, it depends on the initial thickness of blank disk $t_0$. The contribution of the initial thickness of blank disk $t_0$ to the wall thickness of the straight part of the flank surface of formed V-shaped profile $t_w$ is 98.6% with the significant level of 1%.

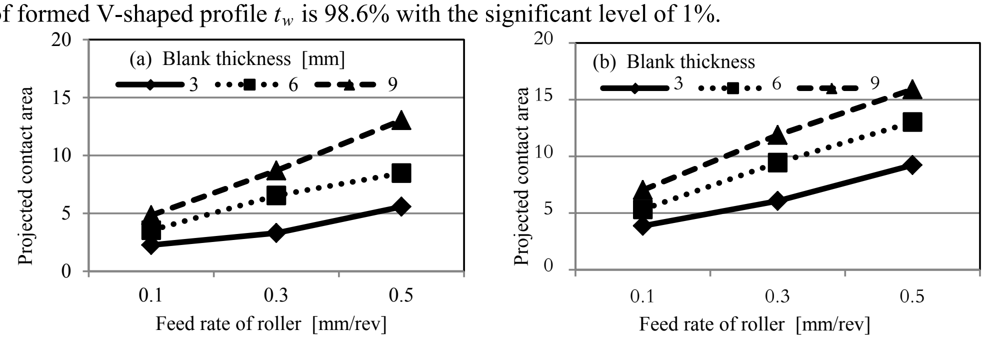


Fig. 5. Effect of initial blank thickness $t_0$ and feed rate of roller $v$ on the projected area of contact $A_p$, (a) $\alpha = 45°$, (b) $\alpha = 60°$.

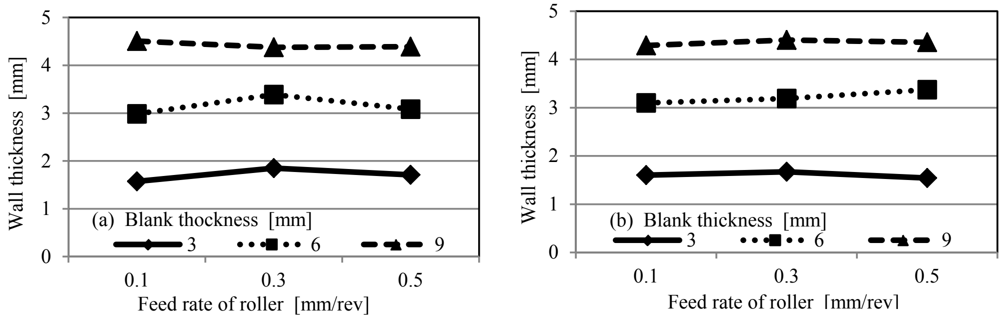


Fig. 6. Effect of initial blank thickness $t_0$, apex angle of forming roller $\alpha$ and feed rate of roller $v$ on the formed wall thickness $t_w$, (a) for $\alpha$ = 30°, (b) for $\alpha$ = 60°.

### 3.2. Asymmetric forming

While the experimental results on symmetric rotary splitting are described in the preceding section, the experiments was also carried out in which the forming roller came into contact with the outer surface of workpiece at the asymmetric position along the thickness with the axial offset $\Delta x$. The thickness of blank disk $t_0$ was 9 mm and the axial offsets $\Delta x$ were 0.5 mm, 1.5 mm and 2.5 mm. The stress-strain relation of the material used in the experiment for asymmetric forming was $\sigma = 153\varepsilon^{0.195}$ MPa. The apex angle of forming angle $\alpha$ and the feed rate of forming roller $v$ were same as symmetric forming.

The normalized radial forces $F_r$ are shown in Fig. 7(a) for the feed rate of forming roller of $v$ = 0.3 mm/rev and Fig. 7(b) for the axial offset of $\Delta x$ = 2.5 mm, respectively. It can be noted that the radial force $F_r$ is independent on the axial offset $\Delta x$ from Fig. 7(a). The radial force $F_r$ increases with the increase in the apex angle of forming roller $\alpha$ and the feed rate of forming roller $v$, as in symmetric rotary splitting. The contributions of the apex angle of forming roller $\alpha$ and the feed rate of forming roller $v$ to the radial force $F_r$ are 60.0% and 36.8%, respectively, with the significant level of 1%.

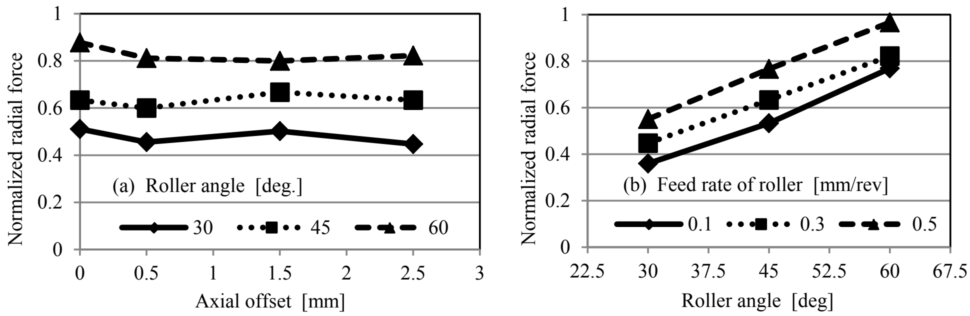


Fig. 7. Effect of axial offset $\Delta x$, apex angle of forming roller $\alpha$ and feed rate of forming roller $v$ on the normalized radial force $F_r$, (a) $v$ = 0.3 mm/rev, (b) $\Delta x$ = 2.5 mm.

There exists the axial force $F_a$ in asymmetric rotary splitting. The normalized axial forces $F_a$ can be shown in Fig. 8(a) for the axial offset of $\Delta x$ = 2.5 mm and Fig. 8(b) for the feed rate of forming roller of $v$ = 0.1 mm/rev, respectively. The axial force $F_a$ increases with the increase in the apex angle of forming roller $\alpha$, the feed rate of forming roller $v$ and the axial offset $\Delta x$. The contributions of the apex angle of forming roller $\alpha$, the feed rate of forming roller $v$ and the axial offset $\Delta x$ to the axial force $F_a$ are 16.1%, 1.7% and 77.1%, respectively, with the significant level of 1%.

The thickness of the part to be formed is also asymmetric in asymmetric rotary splitting. The straight length of thicker part of formed V-shaped profile $l_s$ can be seen in Fig. 9(a) for the feed rate of forming roller of $v$ = 0.1

mm/rev. The straight length of thicker part of formed V-shaped profile $l_s$ increases with the increase in the apex angle of forming roller $\alpha$ and the axial offset $\Delta x$. The contributions of the apex angle of forming roller $\alpha$ and the axial offset $\Delta x$ to the straight length of thicker part of formed V-shaped profile $l_s$ are 16.5% and 71.9%, respectively, with the significant level of 1%. The axial offset $\Delta x$ has a strong effect on the straight length of thicker part of formed V-shaped profile $l_s$. The axial off set $\Delta x$ determines the initial thickness of thicker part and thinner part to be formed $t_i$. Fig. 9(b) shows that the length of the straight part of formed V-shaped profile $l_s$ has an almost linear relationship to the initial thickness to be formed $t_i$ for the apex angle of $\alpha$ = 45°.

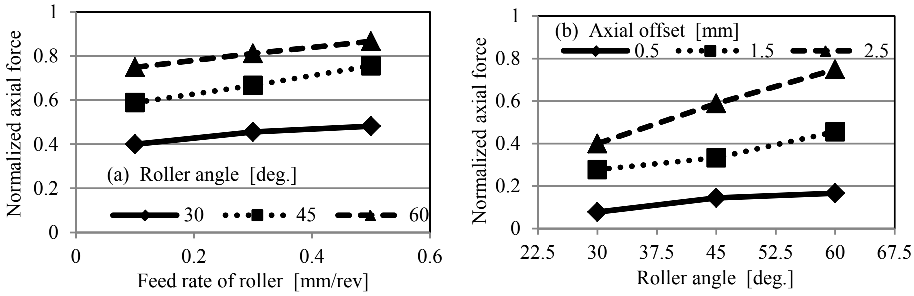


Fig. 8. Effect of axial offset $\Delta x$, apex angle of forming roller $\alpha$ and feed rate of roller $v$ on the normalized axial force $F_a$, (a) $\Delta x$ = 2.5 mm, (b) $v$ = 0.1 mm/rev.

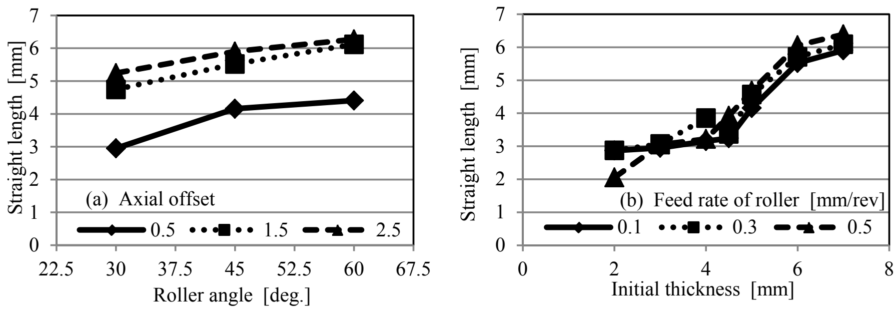


Fig. 9. Effect of axial offset $\Delta x$, apex angle of forming roller $\alpha$ and initial thickness $t_i$ on the length of straight part of formed V-shaped profile $l_s$, (a) $v$ = 0.1 mm/rev, (b) $\alpha$ = 45°.

## 4. Conclusions

The conclusions obtained through the present experiment are summarized as follows:

(1) The radial force in rotary splitting of circular disk $F_r$ increases with the increase in the initial thickness of blank disk $t_0$, the feed rate of forming roller $v$ and the apex angle of forming roller $\alpha$.

(2) The length of the straight part of the flank surface of formed V-shaped profile $l_s$ increases with the increase in the initial thickness of blank disk $t_0$ and the apex angle of forming roller $\alpha$.

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